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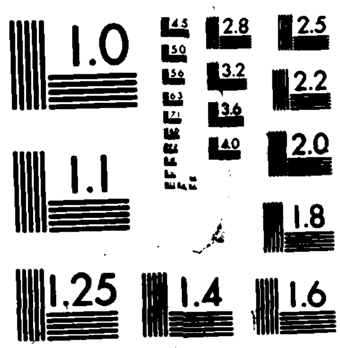

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Fracture Mechanics, Strain Energy Density and Critical Issues for Research and Applications

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This report is in response to a number of requests for a concise review of issues in fracture mechanics, the development of strain energy density concepts within the academic community, and the implications of these issues and concepts for fracture mechanics within the Navy. ~~In writing such a paper,~~ the authors have attempted to highlight the fundamental differences between various criteria, chronologically review the development of strain energy concepts at Lehigh ~~University~~ under Professor George Sih, ~~and close with~~ a brief description of research topics being pursued at the Naval Research Laboratory. In this way, the reader is given the author's perspective leading to the selection of critical issues for fracture mechanics. The forthcoming report "Critical Issues and Directions for Fracture Mechanics and Structural Integrity," similar in format, will concentrate more on the author's current activities and specific technical issues for future applications.

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FRACTURE MECHANICS, STRAIN ENERGY DENSITY AND CRITICAL ISSUES FOR RESEARCH AND APPLICATIONS

Introduction

This report is in response to a number of requests for a concise review of issues in fracture mechanics, the development of strain energy density concepts within the academic community and the implications of these issues and concepts for fracture mechanics within the Navy. In writing such a paper, the authors have attempted to highlight the fundamental differences between various criteria, chronologically review the development of strain energy concepts at Lehigh University under Professor George Sih, and close with a brief description of research topics being pursued at the Naval Research Laboratory. In this way, the reader is given the authors' perspective leading to the selection of critical issues for fracture mechanics. The forthcoming report "Critical Issues and Directions for Fracture Mechanics and Structural Integrity", similar in format, will concentrate more on the current activities within the Fracture Mechanics Section and specific technical issues for future applications.

The discipline of fracture mechanics has developed over the past 65 years in an attempt to better understand the conditions for material fracture and translate this understanding into structural failure prediction. Over this period of time, it was a natural evolution for the many developers of this technology to examine the applicability of fundamental quantities governing structural equilibrium, geometric compatibility and thermodynamics. As a result, theories of material fracture and structural failure have been formulated in terms of stress, strain or energy. The scientific goals over this period of intense effort have been to understand when and why cracks and crack-like defects grow, don't grow or intermittently grow for different geometries, loading conditions and environments. The technology goals of this period have been to translate this understanding into engineering methodologies by identifying parameters associated with fracture that are also applicable to the design and analysis process.

The rapid developments of materials technology and the now extensive use of computers for engineering analysis have forced the continued restatement of the scientific and engineering goals of the fracture mechanics discipline. The fundamental questions which must be answered by any viable fracture mechanics methodology are:

Is the method applicable to different types of materials?

Is the method applicable to different types of structures?

Is the method applicable to different types of loads?

Is sufficient accuracy provided by the analysis for the application?

Will reasonable cost provide sufficient accuracy for the application?

Is this methodology compatible with current and future design philosophy?

Does this methodology relate to previous, current and future material property databases?

Is this methodology a framework with which to consistently address future developments in material, structural and computational technology?

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These questions provide a comprehensive and necessary set of requirements that should be applied to any question of structural integrity.

Any comprehensive approach to fracture mechanics must address (i) the behavior of the material at each point in the body, (ii) the energy balance of the body in its entirety, and (iii) the propagation and arrest of cracks in the body. This means not merely identifying quantities and parameters to describe these aspects of the problem individually, but to identify quantities which are related to one another as they describe the problem as a whole. It is, unfortunately, very tempting to identify one parameter for one type of material, geometry or load history, and apply it, without regard to implicit assumptions, to other problems outside the context in which it was first stated.

Brief Review of Fracture Criteria Introduced Prior to 1972

Conceptually, fracture mechanics should provide a consistent way of reconciling the global energy balance of the structure with the local material response in the vicinity of the crack tip. In the case of linear elastic material behavior, with the mathematical simplification of two-dimensional plane strain deformation which implies self similar crack growth, the energy release rate G follows from basic thermodynamic considerations and the minimization of potential energy, while the material response near the crack tip is traditionally expressed in terms of the stress singularity coefficient, i.e., the stress intensity factor K_I. These two quantities can be related, under the restrictions of linearly elastic material behavior, two-dimensional plane strain deformation and self similar crack growth, as

$$G = \frac{K_I^2(1 - \nu^2)}{E}$$

for a crack in an infinite body loaded in tension perpendicular to the crack. Thus, G describes the global energy behavior while K_I is associated with the geometric and loading influences on the crack tip response.

J-integral also expresses change in potential energy of the system with respect to a self similar crack growth increment. It does so for the case of a 2-D nonlinear elastic body with a crack by utilizing one of the path independent contour integrals of plane elasticity. The result is the J parameter which, in concept, can be calculated from the boundary conditions of a cracked body. The value of J can be related to the energy release rate and K_I factor as

$$J = G = \frac{K_I^2(1 - \nu^2)}{E},$$

for the case of linearly elastic materials.

For ductile metals which exhibit plastic behavior the most important limitations of these three parameters (K, G, J) are the inherent two-dimensionality, the inability to address energy dissipation and the inability to address the nonproportional loading which occurs near the crack tip. While there is little doubt that for weakly ductile materials the restriction to elastic materials, as an engineering approximation, can be relaxed, the other restrictions remain in effect and unavoidable in trying to rationalize G, K, or J concepts. For a diversity of realistic problems of interest and importance the deformation is inherently three-dimensional and non-self similar crack growth will occur. It may be firmly stated that, for material ductility associated with more than five per cent strain or ten percent reduction in area from tensile specimen response, energy dissipation in the vicinity of the crack tip is sufficient to violate the restrictions on G, K and J concepts. This dissipation is not restricted to energy associated with surface generation. It may simultaneously result in load redistribution and non proportionality of the deformation state.

The fundamental issue for ductile engineering materials becomes how to account for the intensity of available elastic energy (which continues to sustain the load) and the intensity of dissipated energy (which manifests as damage to the material) at each point in the body. Some points, of course, will lie

in the path of a growing crack and eventually contribute to fracture surface generation. Most points, however, fall into regions of plastic deformation present in the structure and indirectly influence crack growth by local redistribution, or directly contribute to plastic collapse of the body in the absence of fracture. Efforts to link the relative proportions of crack growth energy and crack tip plasticity energy into a workable fracture parameter have not been successful.

Review of a Strain Energy Density Theory as Developed by George Sih of Lehigh University

The most recent introduction of a new fracture criteria occurred in 1972 when a strain energy density theory of fracture was presented by George Sih of Lehigh University. In the subsequent period of time leading to the present, the theory has evolved in an attempt to explain more physical phenomena related to fracture mechanics and to handle a broader class of engineering applications. Sih's strain energy density theory has, from the outset, been a controversial approach to the fracture problem. It focuses attention on the continuum behavior of the material in the vicinity of the crack tip, rather than on the macroscopic crack length and the applied load. It is stated, in its simplest form, as three hypotheses. Its application tends to appear somewhat more involved than other fracture criteria, although its potential to handle general classes of fracture problems can in theory avoid the misapplication common to other criteria.

The purpose of this discussion is to accurately outline the chronological development of Sih's strain energy density theory, to critically assess its strengths and weaknesses, and to discuss the utility of the general concept to fracture mechanics and material damage mechanics. In doing so, the written development of Sih's strain energy density theory, personal experience with the concept and viewpoints expressed within the fracture mechanics community will be included. It is hoped that the reader will benefit from this type of survey which is not meant to advocate the complete acceptance or denial of a concept, but rather to factually highlight more than one decade of particular effort within a framework utilizing one relevant physical parameter, i.e., strain energy density.

The evolution of Sih's strain energy density criterion for fracture can, for purpose of review, be separated into four distinct, and somewhat overlapping, periods. Each period features a set of critical goals and issues, and was a prerequisite for subsequent efforts. Specifically, these four periods are: Linearly elastic fracture mechanics (1972-1977), Elastic-plastic fracture mechanics, (1977-1982), Isothermal damage mechanics (1981-1984), and thermodynamic damage mechanics (1983-present). However, the underlying theme throughout each of these periods is that fracture should be described at an appropriately small (i.e., continuum) scale using a scalar physical parameter (i.e., energy density). The use of energy density to govern continuum failure due to fracture also can assess energy dissipation from the onset of yielding to final fracture of the continuum.

In 1972, Sih first presented his strain energy density theory in a form primarily for linearly elastic materials. Material toughness was defined in terms of the critical strain energy density absorbed by the material to produce fracture. This value was stated to be a constant for a given material, and can be calculated from material response as

$$\left(\frac{dW}{dV}\right)_c = \int_0^{\epsilon_c} \sigma \, d\epsilon$$

where $(dW/dV)_c$ is the critical strain energy density, σ is uniaxial stress, ϵ is uniaxial strain, and ϵ_c is uniaxial strain at fracture. This value of material toughness is assumed to govern fracture initation as well as crack growth by monotonically increasing loads since it is independent of any crack length parameter.

The strain energy density in a multiaxial state of deformation is given by the following expression (in terms of stresses) for linearly elastic materials,

$$\left(\frac{dW}{dV}\right) = \frac{1}{2E} (\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2) - \frac{\nu}{E} (\sigma_{xx}\, \sigma_{yy} + \sigma_{yy}\, \sigma_{zz} + \sigma_{zz}\, \sigma_{xx})$$

$$+ \frac{1+\nu}{E} (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)$$

where the σ_{ij}'s and τ_{ij}'s are the components of stress, and ν and E the elastic constants of the material.

The energy density field in the immediate vicinity of the crack tip, in the case of linear elastic material response, is given by the expression

$$\left(\frac{dW}{dV}\right) = \frac{S}{r}$$

where S is called the strain energy density factor, and r is the radial distance from the crack tip. Restricting the discussion to the two dimensional case, for purposes of illustration only, the S factor is a function of the local angular coordinate θ, the stress intensity factors k_i^*, and the material elastic constants. The S factor takes the form

$$S = a_{11} k_1^2 + 2a_{12} k_1 k_2 + a_{22} k_2^2$$

where the a_{ij} coefficients reflect the θ, E and ν dependence. The S factor analytically features the mixed mode stress intensity factors, which result directly from the form of the singular strain energy density field in the vicinity of the crack tip.

Crack instability and growth are governed by the following hypotheses:

(I)Crack initiation takes place in a direction determined by the local minimum value of the strain energy density factor, i.e.,

$$\frac{\partial S}{\partial \theta} = 0 \text{ and } \frac{\partial^2 S}{\partial \theta^2} < 0 \text{ at } \theta = \theta_0.$$

(II)Crack extension occurs when the strain energy density factor reaches a critical value, i.e.,

$$S\ (k_1, k_2) = S_c \text{ for } \theta = \theta_0$$

Thus, the direction of crack growth is determined first, followed by the calculation of critical S_c from the k_i factors for the problem. If one associates a critical length parameter r_c with the fracture event, then the condition

$$\left(\frac{dW}{dV}\right)_c = \frac{S_c}{r_c}$$

will hold. In this manner, a continuum toughness parameter $(dW/dV)_c$ is related to a crack growth length parameter r_c and the macroscopic crack length and applied load parameter S_c.

Sih discusses Hypothesis I in terms of the relative dilational and distortional character of the energy density field for a fixed value of r. The minimum value of S is closely associated with dilatation, favoring fracture in this direction. Sih makes a fundamental point that the scalar decomposition of dilational and distortional energies from the total energy is incorrect. The energy density must be treated as a whole and simultaneously account for fracture and yielding. This point is not agreed upon by investigators who separate the energy in order to independently associate fracture with dilatation and yielding with distortion. However, difficulties in separating the terms become apparent, in general, when nonlinearity is present. This fact favors Sih's argument.

*Sih's analytical expression for the stress intensity factors k_i differ by a factor of $\sqrt{\pi}$ from the more widely used K_i factor (e.g., $K_1 = k_1\sqrt{\pi}$). Appropriate conversion should be made as required.

Two dimensional analytical predictions and experimental investigations have been conducted on relatively brittle materials to predict the angle of crack growth and critical load. The experimental results compare favorably to the predicted results. The use of strain energy density to predict crack growth direction and instability for such materials is, on the basis of these studies, relatively common in the applications community. Other theories are also used, such as maximum tangential stress and maximum energy release rate. Questions of general applicability do, in many ways, favor the use of strain energy density.

The second phase of development in the strain energy density theory began in 1977 and proceeded through 1983. This phase concentrated on elastic-plastic fracture using classical theories of plasticity to account for material nonlinearity. General shortcomings of continuum plasticity theory were frequently discussed, including the scalar decomposition of elastic and plastic strain and the influence of material test specimen size and loading effects. Plasticity theory was used as a means by which material nonlinearity could be introduced into crack growth predictions in the absence of a more satisfactory constitutive formulation.

This phase of development also saw a shift from the the use of closed form analytical solutions for crack and notch problems to the use of finite element analysis for finite boundary problems and three-dimensional problems involving non-self-similar crack growth and material nonlinearity. The emphasis in addressing stable crack growth, as opposed to the initiation of crack growth, required the shift to finite element techniques. Analyses were done using modified APES and PABST finite element codes (initially developed by the Navy at DTNSRDC/Carderock and at Lehigh University), or the three dimensional version of APES, named TRID.

Stable crack growth increments under monotonic loading were governed by the relation

$$\left(\frac{dW}{dV}\right)_c = \frac{S_1}{r_1} = \frac{S_2}{r_2} = \ldots$$

where the S_i and r_i refer to the values of strain energy density factor and crack growth increment at a particular value of the load. In practice, the intersection of the energy density function (plotted as a function of radius in the direction of crack growth) with the critical energy density value determines the crack growth increment r_i. The S_i factor is calculated from r_i and $(dW/dV)_c$ for each increment of growth.

If the crack is tending toward instability,

$$S_1 < S_2 < \ldots < S_c$$

while if the crack is tending toward arrest,

$$S_1 > S_2 > \ldots > S_a$$

where S_a would be considered a crack arrest parameter.

The strain energy density concept was applied to three classes of problems during this period. The first was the planar, but non-self-similar crack growth of the type frequently found in center cracked panels and compact tension specimens made of ductile materials. The development of crack tunneling was simulated by incremental crack growth in three-dimensional finite element models. The amount of growth at each point along the crack front was determined by the simultaneous application of the strain energy density crack growth criterion.

The second problem addressed involved two-dimensional fatigue crack growth under small scale yielding. Path dependency of the fatigue crack growth on load history was numerically demonstrated. The application of strain density concepts to fatigue crack growth involves hysteresis energy during a cycle of loading, and its accumulation over many cycles that leads to local material fracture. The use of the S factor to generate a fatigue crack growth parameter $\Delta S/\Delta a$ was also presented at this time.

The final problem considered in elastic-plastic fracture using classical theories of plasticity involved the parametric investigation of size and rate effects on observed deformation and fracture. The specimen geometries and crack growth considered were similar to those in the three-dimensional problem discussed above. The reason for undertaking such a parametric study was to understand the relative brittle and ductile behavior observed by geometrically similar specimens of different sizes, and the similar phenomenon observed for specimens loaded at different loading rates.

It is perhaps appropriate to discuss the manner in which the term "loading rate" is used in the incremental crack growth studies done at Lehigh University since it has been a frequent source of confusion. Physically and analytically, rate dependence by definition requires an explicit dependence upon time. In the numerical studies done under George Sih, rate dependence has not been used in this sense, but in terms of the relative amounts of crack growth versus material plasticity admitted during one quasi-static loading increment. A high loading rate, by this definition, implies a smaller amount of stable crack growth. A low loading rate, by this definition, implies a larger amount of stable crack growth. This trend was implemented using the loading step size for each analysis. A larger step size to cover a given loading range means fewer crack growth increments. A smaller step size to cover the same loading range will mean more crack growth increments. The question of uniqueness of solution and the relation between physical loading rate, associated with physical time, and numerical loading rate, without a time scale as used in these studies, is apparent. While this disgression is not meant to justify the rate issue, it hopefully can clarify it for purposes of discussion.

The first significant and important departure from classical continuum mechanics was the assertion that different constitutive parameters should be introduced in different regions of the solid body. Stated conversely, this statement says that a chemically homogeneous material body should be treated as materially inhomogeneous from point to point. This position was taken in light of persistent numerical results that produced physically unrealistic crack fronts over the range of specimen geometries considered. Instead of crack tunneling featuring one central point of maximum penetration, tunneling with two symmetric points of maximum penetration were consistently produced from numerical simulations conducted with one set of constitutive parameters. Modification of yield stress and Ramberg-Osgood coefficients in the material through the specimen thickness, however, produced results qualitatively similar to the physical characteristics of tunneling phenomenon.

The third phase of strain energy density theory development can be classified under the theme of isothermal damage mechanics. It covered the period from approximately 1981 to 1984. The fundamental goals of this period of effort were to define a relative, local material toughness and to examine the explicit treatment of material nonlinearity and fracture by energy density based constitutive responses of the materials.

The need for a relative, local definition of material toughness is required for stable crack growth since many practical situations involve crack growth into already yielded material. The yielding process can be expected to reduce the material's resistance to fracture at the continuum scale. The relative critical energy density $(dW/dV)_c^*$ was defined as

$$\left(\frac{dW}{dV}\right)_c^* = \left(\frac{dW}{dV}\right)_c - \left(\frac{dW}{dV}\right)_d$$

where $(dW/dV)_d$ is the energy dissipated during the loading history prior to fracture. Every material point in the body has a relative critical energy density value at each instant during the loading process. This represents a modification to the fracture criterion as stated earlier.

The stable crack growth relationship is accordingly modified to

$$\left(\frac{dW}{dV}\right)_c^* = \frac{S_i^*}{r_i^*} = \frac{S_2^*}{r_2^*} = \dots$$

where the $(\ )^*$ quantities refer to the current state of the material immediately ahead of the tip for the current crack growth increment.

Analyses were conducted for the simple case of a pseudo-elastic material. Such a material exhibits nonlinear behavior beyond yield, but will linearly unload back to the original state without a residual strain. A material which experiences significant, diffuse microcracking, at a scale below the continuum scale, prior to macrocracking will exhibit such behavior. The results of finite element analyses demonstrated the relative sensitivity of global nonlinearity and instability due to the small scale dissipative mechanism, stable crack growth and the combined influence of these two effects. Parametric studies on size and rate effects in cylindrical specimens with circular macrocracks were also numerically simulated.

Another set of analyses were conducted using the relative critical energy density concept in conjunction with elastic-plastic material behavior using traditional constitutive assumptions for plasticity. Welded sections were numerically modeled to predict crack growth directions.

The fourth phase of strain energy density theory development at Lehigh University is currently in progress. This thermodynamic damage mechanics is directed toward the development of a formulation which accounts for energy dissipation in the mechanical and the thermal regimes, and the relative interactions of these quantities.

The essential features of the theory involve the decomposition of the strain energy density W into a dissipated energy term D and an available energy term A. Incrementally,

$$dW = dD + dA, \frac{dD}{dt} \geqslant 0.$$

The positive definite nature of the dissipation rate is ensured by the associated inequality condition.

The material constitutive response is postulated to be an unknown at each point of the body. The responses, are constructed from uniaxial tensile specimen responses which form a "databank" of material behaviors covering different rates and deformation states. Deformation is postulated to be governed by the uniaxial strain ϵ and the ratio of volume change to surface area change at a point, dV/dA. The uniaxial databank is constructed in such a way that

$$\frac{d\sigma}{d\epsilon} = \lambda \frac{dV}{dA}$$

where $d\sigma/d\epsilon$ is the tangent to the stress strain curve and λ is a proportionality factor. The functional dependence and form of λ is not known. It has been assumed constant in analyses to date. Stress states at each instant of the load history are constructed using the databank. The strain energy density function follows as

$$\frac{dW}{dV} = \int \sigma d\epsilon = \int\int \lambda \left(\frac{dV}{dA}\right) d\epsilon\, d\epsilon.$$

Material damage leading to fracture is assumed to define a "plane of homogeneity." The plane of homogeneity at each point of a structural component must be determined by matching its state of deformation in the databank. Material failure is assumed to occur such that

$$\left(\frac{dW}{dA}\right)_i = \left(\frac{dV}{dA}\right)_i \left(\frac{dW}{dV}\right).$$

This formulation associates the surface energy density $(dW/dA)_i$ vector with the scalar volume energy density (dW/dV) through the local volume to area ratio vector $(dV/dA)_i$.

This formulation has been applied to the analysis of incremental crack growth and the heating and cooling of round bars under tensile load, as well as to problems outside solid mechanics (e.g., fluid

flow). The results which have been produced on the basis of this postulated formulation are, for the classes of problems considered, in general qualitative agreement with observed physical phenomena. The quantitative agreement is not sufficient, with the results given to date, to validate the formulation for engineering use.

Certain conceptual issues may, in fact, need to be resolved. The concepts presented in this last phase of developments, as pursued at Lehigh University, are controversial and represent a radical departure from the traditional concepts of plasticity, fracture and thermodynamics. Close examination of the details of the theory, in its present form, raises questions regarding consistency, governing assumptions, and experimental verification. The above comments concerning the λ parameter is such an example, and may be one factor responsible for quantitative discrepancies between prediction and observation. To date, the domain of application has been restricted to small strains. Demonstration of the concepts in problems involving larger strains would be necessary to validate general applicability. In view of these comments, the appropriate formulation of Sih's approach is not apparent at this time.

The issues raised by Sih in the presentation of his criterion are valid. Progress in this area of solid mechanics will only be made by major revisions in the way fundamental issues of material behavior and structural analysis are approached.

A Perspective on Fracture Mechanics Issues in the Navy

The authors have been examining energy density concepts in a concerted attempt to overcome the inherent limitations of commonly used fracture criteria for thin section applications of ductile materials. The use of a local toughness definition, based on a state variable such as energy density, has become a practical methodology for the analysis of welded structures conducted by members of the section. The success in addressing the types of problems which are intractable by other fracture methodologies suggests that significant gains in the fundamental understanding of the fracture process and significant gains in the application of this understanding to structural analysis and design will follow.

Significant issues must be addressed to gain this understanding. Perhaps the most significant issues are the analytical modeling and physical assessment of material behavior for anticipated deformation histories. Experience gained in material assessment and failure prediction suggest that continuum behavior at large deformations requires an appropriate treatment. The overwhelming amount of work being done today remains in the small strain realm, with limited use in ductile fracture. Extrapolation of these results is commonplace, but ongoing analyses conducted at NRL indicate the danger in this assumption. For this reason, extensive efforts are being focused on a combined experimental-computational approach to reconstructing local continuum events from standard test specimens subjected to large deformations.

Strain rate effects in material behavior and their influence on crack growth and structural integrity are being examined in the context of viscoplasticity theories. Explicit time dependence of material behavior must be accurately reflected in numerical procedures for structural integrity, as well as for designing material testing and data analysis procedures. The number of parameters and functional form of the equations make material testing for viscoplastic characterization a complex issue. Current investigations in solid mechanics may provide a framework in which to rationally reduce the testing procedure to an appropriate number for full characterization.

Material damage modeling is proceeding in order to accurately quantify and translate the dissipation energy at each point in a structure to a local toughness definition which explains observed fracture phenomena. This links the material scale to the fracture scale in a manner consistent with current analysis techniques. If done correctly, significant progress on the long standing problem of translating complicated load histories (featuring static, thermal, fatigue and dynamic loads) to accurate structural integrity prediction will be made.

The authors' view is that no comprehensive description of the fracture process currently exists that can satisfy the requirements that were posed at the outset of this discussion. There is a considerable amount of past work in the fracture mechanics community, a considerable amount currently in progress, and surely an additional amount to come in the future. Portions of this overall effort in the subject area will be of use to the Navy's needs, while a significant amount will offer little progress toward achieving the goals presented here.

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